NAVAL HEALTH RESEARCH CENTER

BODY TEMPERATURE AND FIREFIGHTER ENSEMBLE TEMPERATURES DURING EXERCISE AND EXPOSURE TO MODERATE WARM, AND HOT AIR TEMPERATURES

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Body Temperatures and Firefighter Ensemble Temperatures during Exercise and Exposure to Moderate, Warm, and Hot Air Temperatures

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Human subjects participated in this study after giving their free and informed consent. This research has been conducted in compliance with all applicable Federal Regulations governing the Protection of Human Subjects.

Summary

Problem

The relationships among rectal and skin temperatures during exercise and naval firefighter ensemble (FFE) garment temperatures during exposure to moderate, warm, and hot air temperatures has not been established.

Objective

The purpose of this study was to evaluate the relationships among FFE temperatures and body temperatures during exercise in moderate, warm, and hot air temperatures.

Approach

Male subjects (*n*=10) attempted to complete three trials of 20-min rest, 20-min exercise, 20-min recovery, 20-min exercise, and 20-min recovery. Subjects wore complete FFE and respired using a positive-pressure breathing apparatus. Exercise consisting of treadmill walking ($1.1\ m \cdot s^{-1}$/0% grade) occurred in 50% relative humidity (RH) and dry-bulb (T_{db}) air temperatures of 21°C (MOD), 35°C (WARM), and 49°C (HOT), while seat rest and recovery occurred in 27°C air. Measurements included heart rate (HR), rectal (T_{re}), and skin temperatures from the upper right chest (T_{ch}), right upper arm (T_{ar}), right midlateral thigh (T_{th}), and right midlateral calf (T_{ca}). Calculations included mean skin temperature (T_{msk}) and body heat storage (HS). Thermistors placed on the outer surfaces of the chest (T_{oc}) and thigh (T_{ot}) regions, middle-fabric layers of the chest (T_{mc}) and thigh (T_{mt}) regions, and inner surface of the chest (T_{ic}) and thigh (T_{it}) regions recorded FFE temperatures. T_{oc} and T_{ot} were averaged to produce an outer (T_O) FFE temperature, T_{mc} and T_{mt} were averaged to produce a middle (T_M) FFE temperature, and T_{ic} and T_{it} were averaged to produce an inner (T_I) FFE temperature. Data were analyzed by repeated-measures analysis of covariance (ANCOVA). Regression analysis was also conducted to determine the relationship among steady-state FFE and T_{msk} obtained during the second exercise period.

Results

All subjects completed the 100-min test during the MOD and WARM trials. However, only 4 subjects completed the HOT trials. During the HOT trials, 6 subjects were stopped within 6 min

of completing the second exercise period due to HR exceeding 90% maximum HR because the subjects felt "very hot." ANCOVA revealed (1) significant trial, exercise period, and trial-by-exercise period effects for HR, T_{re}, and HS; (2) significant trial and trial-by-exercise period effects for T_{msk}; and (3) significant trial effects for T_O, T_M, and T_I FFE temperatures.

During the initial rest period of all trials, seated HR averaged 78 ± 10 beats per minute (bpm). During MOD, exercise HR averaged 111 ± 13 bpm for both exercise periods. During WARM, exercise HR averaged 124 ± 13 bpm in the first exercise period, and increased to an average of 135 ± 20 bpm during the second exercise period. During HOT, exercise HR averaged 146 ± 13 bpm in the first exercise period, and 159 ± 27 bpm during the second exercise period.

During MOD, temperatures were highest for T_{re} (37.2°C), followed by T_{msk} (36.5°C), T_I (30.8°C), T_M (29.5°C), and T_O (24.9°C). During WARM, T_O, T_M, and T_I were equivalent (35.6°C), and lower than T_{msk} (36.1°C), and T_{re} (37.2°C and 37.6°C for first and second exercise periods, respectively). During HOT, temperatures were highest for T_O (45.6°C), followed by T_M (41.5°C), T_I (40°C), and T_{msk}, (38°C and 38.6°C for first and second exercise periods, respectively), and T_{re} (37.4°C and 38.2°C, respectively). Total fluid intake, total-body sweat loss, and fluid balance were significantly different for HOT compared with MOD and WARM.

<u>Conclusion</u>

Our findings suggest that exercise T_{re} in subjects wearing FFE is related to dry-bulb temperature and heat storage. When T_{db} is above skin temperature, exercise skin temperatures are primarily related to the T_{db}-FFE temperature gradient. When T_{db} is lower than skin temperature, FFE temperatures are dependent on the skin temperature-T_{db}, gradient. However, work/recovery cycles accelerate modified body temperature responses. FFE garment temperatures without the presence of the human body rapidly equilibrate with T_{db}. These findings suggest that FFE temperatures change slowly during exercise because air movement within and around the FFE is hindered in the presence of a human body. This information may predict stay times during exposure to extreme conditions. This information has implications for the development of future FFE designs, and the construction of heat strain models.

Introduction

The firefighting ensemble (FFE) is a heavy and bulky overgarment designed to protect against flames, smoke, and radiant heat. During physical activity, the high insulation and low water permeability coefficients of the FFE hinder heat dissipation, and increase heat strain and heat storage (Pimental, Avellini & Banderet, 1991; Romet & Frim, 1987; Skoldstrom, 1987). However, little is known of FFE temperature gradients through the garment during physical activity and exposure to environmental stressors, or of the relationship between these gradients and body temperature responses. Information on thermal temperature gradients within the FFE during physical activity and exposure to moderate to high heat conditions may prove useful in developing better predictive models of heat strain and physical performance. The purpose of the present study was to determine the relationships among body temperatures and FFE garment temperatures during exercise and exposure to moderate, warm, and hot air temperatures.

Methods

Subjects

Ten males, all trained in shipboard firefighting procedures and use of firefighting equipment, served as subjects. The physical characteristics of the subjects were age, 28.9 ± 4.8 years; height, 179.1 ± 6.6 cm; weight, 88.6 ± 11.1 kg; body surface area, 2.07 ± 0.14 m^{-2}; and body fat 17.1 ± 6.1%. Balke and Ware (1959) maximum treadmill performance time averaged 17.6 ± 2.9 min. Peak heart rate (HR) for the test averaged 188 ± 11 beats per minute (bpm), while peak oxygen uptake averaged 45 ± 6 $ml \cdot kg^{-1} \cdot min^{-1}$.

Medical Screening

Each subject gave his informed consent prior to participation in testing. All subjects underwent medical screening. Medical screening included a medical history questionnaire, body composition assessment, resting 12-lead electrocardiogram (ECG), and maximal exercise stress test. Body surface area, in meters squared, was calculated according to the height and weight regression equation of DuBois (Carpenter, 1964). A U.S. Navy regression equation was used to calculate body fat percentage using height and measures of neck and abdomen circumference (Hodgdon & Beckett, 1984).

ECG electrodes were placed on each subject's chest in the Mason-Liker configuration. Two electrodes were placed on the upper chest near the shoulders (infraclavicular fossa), and two others slightly above the waist. Six electrodes (V_1-V_6) were also placed on the chest in the precordial position around the lower border of the left chest. Resting ECGs and blood pressures (BP) were taken in supine, seated, and standing conditions. All subjects completed an incremental treadmill exercise test to voluntary exhaustion using the Balke and Ware (1959) protocol. Energy expenditure was measured using a metabolic measurement system (SensorMedics, Inc., Model 2900, SensorMedics Corporation, Yorba Linda, CA). Peak HR and oxygen uptake were determined as the highest values obtained during the test. Each minute of recovery, the subject's HR and BP were monitored until they returned to resting values.

Experimental Procedures

Each subject participated in three test trials. The tests were administered in a counter-balanced order. During each test, subjects wore a T-shirt, coveralls, socks, and combat boots as the basic undergarment, and the standard U.S. Navy FFE, including flash hood, hard helmet, gloves, and single-piece Nomex™ firefighting protective suit. Subjects respired using a Dräger positive-pressure self-contained breathing apparatus (SCBA). Total clothing and SCBA weight prior to entry to the first exercise period averaged 23 kg for all tests.

The previous night and the morning of the heat-exposure test, subjects were instructed to drink generous amounts (at least 1 L) of fluid (noncaffeinated) to ensure normal body hydration. Hydration status was determined by measuring the specific gravity of urine samples obtained prior to the test. All subjects were adequately hydrated before beginning each test.

The test protocol used in this study was designed to simulate an activity pattern similar to a shipboard fire suppression operation requiring repeated cycles of exercise and recovery. The protocol consisted of 20-min periods of seated rest, exercise, seated recovery, exercise, and seated recovery. The ambient environment during the initial seated rest period and during the two recovery periods was 27°C. The two exercise periods were conducted inside an environmental chamber. Exercise consisting of treadmill walking ($1.1\ m \cdot s^{-1}$ on 0% grade) occurred in 50%

relative humidity (RH) air and at temperatures of 21°C (MOD), 35°C (WARM), and 49°C (HOT). Ambient conditions inside the chamber were monitored continuously for RH, dry-bulb (T_{db}), wet-bulb (T_{wb},), black-globe (T_{bg}) temperatures, while conditions outside of the chamber were monitored for T_{db}.

During the initial rest period, subjects sat in a chair dressed in FFE with arms inserted in the sleeves and ensemble unzipped down to the waist. During the first and second recovery periods, subjects sat with the FFE open, arms withdrawn from the sleeves, and the FFE pulled off the shoulders to the waist. During the rest and recovery periods, subjects breathed room temperature air. Approximately 3 min prior to starting the first and second exercise periods, subjects stood, zipped- and buttoned-up the FFE, and strapped on and activated the SCBA. Subjects respired from the SCBA throughout the exercise periods.

Measurements

Prior to the test, subjects inserted a rectal thermistor to a depth of 20 cm in the rectum for measurement of rectal temperature (T_{re}). Skin temperatures, using thermistors, were measured from the upper right chest (T_{ch}), right upper arm (T_{ar}), right midlateral thigh (T_{th}), and right midlateral calf (T_{ca}). To record FFE garment temperatures the thermistors placed on the outer surfaces of chest (T_{oc}) and thigh (T_{ot}) regions, middle-fabric layers of the chest (T_{mc}) and thigh (T_{mt}) regions, and inner surface of the chest (T_{ic}) and thigh (T_{it}) regions recorded FFE garment temperatures.

HR was recorded using a Polar Heart Watch System (Polar USA, Inc., Stamford, CT). Energy expenditure (EE) was determined from measures of oxygen (O_2) uptake and carbon dioxide (CO_2) production, expressed in watts (W). During these measurements, subjects respired air from a standard compressed-gas cylinder and a facemask. Modifications to the facemask were made allowing measurement of both inspired and expired O_2 and CO_2. Inspired O_2 and CO_2 were collected from a ⅛" inner diameter plastic tube placed inside the facemask and positioned immediately in front of the lips, while expired O_2 and CO_2 were obtained from a 1" inner diameter rubber tube attached to the expiration post of the facemask. Inspired and expired gases were measured using Ametek CD-3 and S-3A/II analyzers, respectively (Ametek, Pittsburgh, PA). Signals from the analyzers were recorded on a Soltec multichannel chart recorder (Soltec Inc., San

Fernando, CA). Pulmonary ventilation was measured from expired gas flow using a Rayfield gas meter and chart recorder.

We recorded HR, T_{re}, T_{ch}, T_{ar}, T_{th}, T_{ca}, T_{oc}, T_{ot}, T_{mc}, T_{mt}, T_{ic}, and T_{it} at 1-min intervals using an automated data recording and storage computer system. Pretest and posttest nude body weights as well as fluid intake and urine output were recorded to determine change in body weight. During the initial rest and recovery periods, subjects were allowed to drink as much water (21°C) as desired.

The following criteria were used for removal of the subject from heat exposure: T_{re} of 39.5°C; systolic BP of 29.3 kPa (220 mm Hg) or diastolic BP of 16 kPa (118 mm Hg); exercise HR of 90% or greater for 5 min; absence of sweating or presence of chills, nausea, weakness, or dizziness; or subject desiring to terminate the test.

Mean skin temperature (T_{msk}) was calculated from T_{ch}, T_{ar}, T_{th}, and T_{ca} using a weighted equation (Ramanathan, 1964). Mean body temperature (T_{mb}) was calculated using T_{re} and T_{msk} according to a weighted regression equation (Stolwijk & Hardy, 1966). Body heat content (BHC) was calculated using T_{mb}, body weight in kilograms, and the specific heat of the body ($3.48\ kJ \cdot kg^{-1} \cdot C^{-1}$). Heat storage (HS) ($kJ \cdot kg^{-1}$) equaled the difference in BHC from resting to peak values. The outer, middle, and inner chest and thigh FFE temperatures were averaged to create mean outer (T_O), middle (T_M), and inner (T_I) FFE temperatures, respectively. Total-body sweat loss was calculated as the difference between pretest and posttest body weights, with the posttest weight corrected for fluid input and urine output. Fluid balance ($L \cdot h^{-1}$) was calculated as the difference between fluid intake and urine and sweat loss.

Statistical Analysis

We analyzed HR, T_{re}, T_{msk}, HS, T_O, T_M, and T_I for the main effects of trial (MOD, WARM, HOT), exercise period (first, second), and the interaction of trial and exercise period by repeated-measures analysis of covariance (ANCOVA). In these analyses, 10 subject responses occupied each Latin square. Posthoc analyses in the presence of a significant omnibus F-ratio included Student-Newman-Keuls comparisons to evaluate significant differences between trials and exercise periods.

The significance level was set at $p<.05$. Regression analysis was used to evaluate the relationships among T_{msk}, T_O, T_M, and T_I.

Results

All subjects completed the 100-min test during the MOD and WARM trials. However, only 4 subjects completed the HOT trials. During the HOT trials, 6 subjects were stopped within 6 min of completing the second exercise period due to HR exceeding 90% maximum HR, or because the subject felt "very hot."

ANCOVA results of the effects of trial, exercise period, and interaction of trial and exercise period on HR, EE, T_{re}, T_{msk}, HS, T_O, T_M, and T_I are shown in Table 1.

Table 1. Effect of Trial, Exercise Period, and Interaction of Trial and Exercise Period on HR, EE (W), T_{re}, T_{msk}, HS, T_O, T_M, and T_I

Variable	Trial	Exercise Period	Trial x Exercise Period
HR	$p<0.0001$	$p<0.0001$	$p<0.0001$
EE	$p<0.04$	$p<0.0001$	n.s.
T_{re}	$p<0.0001$	$p<0.0001$	$p<0.0001$
T_{msk}	$p<0.0001$	n.s.	$p<0.0001$
HS	$p<0.0001$	$p<0.0001$	$p<0.0001$
T_O	$p<0.0001$	n.s.	n.s.
T_M	$p<0.0001$	n.s.	n.s.
T_I	$p<0.0001$	n.s.	n.s.

Note. n.s. = nonsignificant

Mean HR for the three trials are shown in Figure 1. ANCOVA revealed significant trial, exercise period, and trial-by-exercise period effects for HR. During the initial rest period, seated HR averaged 78 ± 10 bpm for all trials. During MOD, exercise HR averaged 111 ± 13 bpm for both exercise periods. During WARM, exercise HR averaged 124 ± 13 bpm during the first exercise, and increased to 135 ± 20 bpm during the second exercise period. During HOT, exercise HR averaged 146 ± 13 bpm during the first exercise period, and 159 ± 27 bpm during the second exercise period. There was a significant trial effect for EE, with the mean exercise response for HOT (348 W) greater than WARM (330 W) and MOD (320 W).

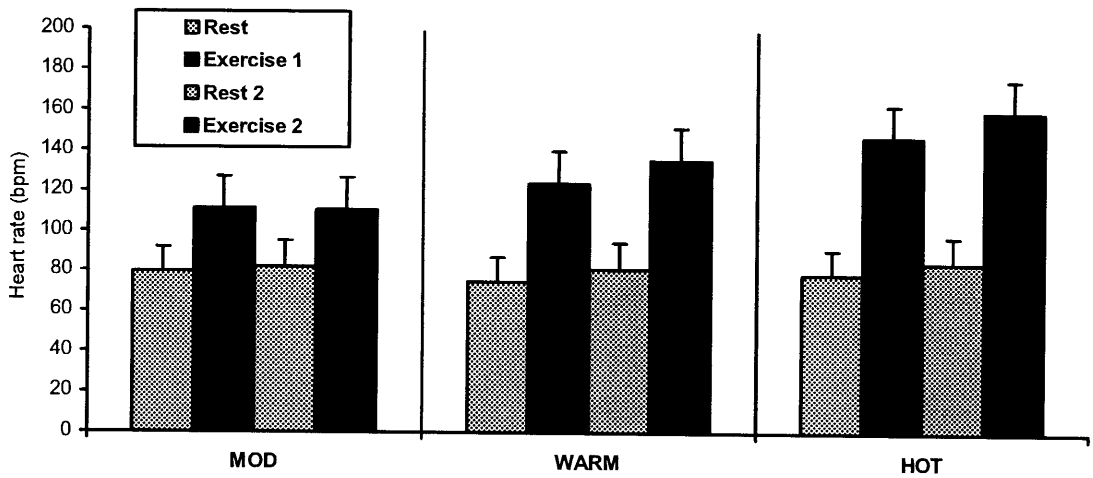

Figure 1. Heart rate during rest and exercise for MOD, WARM, and HOT trials.

Mean T_{re} during MOD, WARM, and HOT are shown in Figure 2. ANCOVA showed significant trial, exercise period, and trial-by-exercise period effects for T_{re}. At the end of the initial rest period for all trials, T_{re} averages 37.2 ± 0.4 °C. During MOD, exercise T_{re} averaged 37.2 ± 0.3°C for both exercise periods. During WARM, exercise T_{re} remained at 37.2 ± 0.3°C during the first exercise period, but increased slightly to 37.6 ± 0.4 °C during the second exercise period. During HOT, exercise T_{re} increased to 37.4 ± 0.3°C during the first exercise period, and further increased to 38.4 ± 0.5°C during the second exercise period.

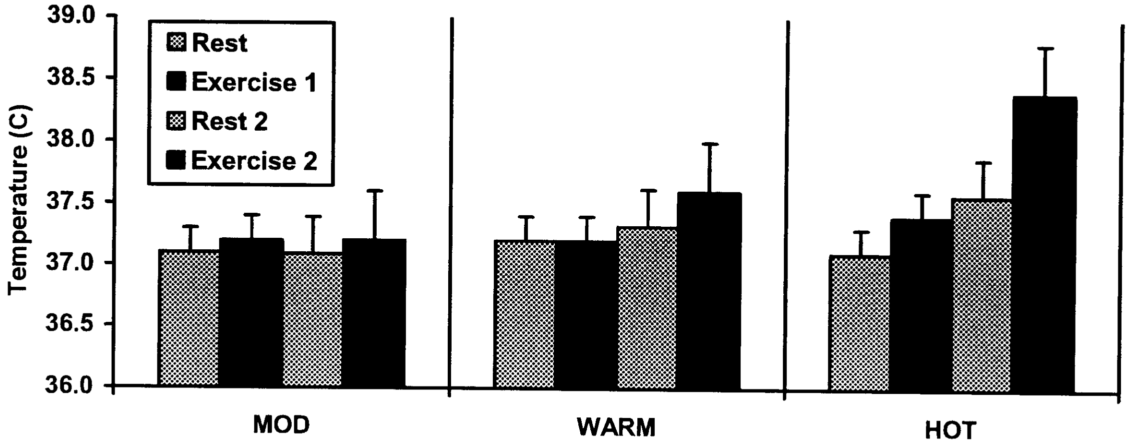

Figure 2. Rectal Temperature During Rest and Exercise for MOD, WARM, and HOT trials.

Mean T_{msk} during MOD, WARM, and HOT are shown in Figure 3. There were significant trial and trial-by-exercise period effects for T_{msk}. At the end of the initial rest period for all trials, T_{msk} averaged 33.9 ± 0.8°C. During MOD, exercise T_{msk} averaged 34.4 ± 0.5°C during the first exercise period, and then dropped to 33.9 ± 0.8°C during the second exercise period. During WARM, exercise T_{msk} averaged 36.1 ± 0.3°C during both exercise periods. During HOT, exercise T_{msk} increased to 38.0 ± 0.4°C during the first exercise period, and then to 38.6 ± 0.5°C during the second exercise period.

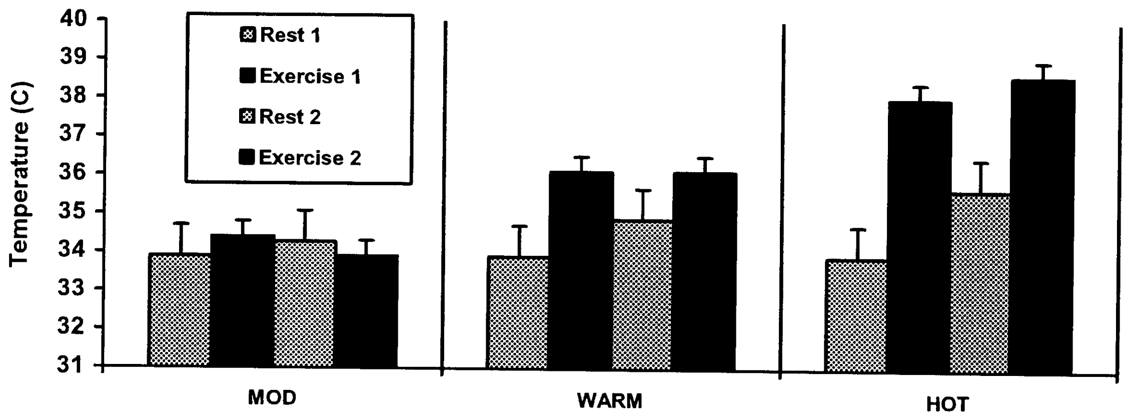

Figure 3. Mean Skin Temperature during rest and exercise for MOD, WARM, and HOT trials.

Mean HS during the first and second exercise periods for MOD, WARM, and HOT are shown in Figure 4. There were significant trial, exercise, and trial-by-exercise period effects for HS. During MOD, exercise HS averaged 0.7 ± 0.7 kJ · kg^{-1} for the first exercise period, and then decreased to 0.1 ± 2.0 kJ · kg^{-1} for the second exercise period. During WARM, exercise HS averaged 1.5 ± 0.3 kJ · kg^{-1} in the first exercise period, and increased to 2.5 ± 0.8 kJ · kg^{-1} during the second exercise period. During HOT, exercise HS averaged 3.9 ± 0.8 kJ · kg^{-1} in the first exercise period and 6.7 ± 1.2 kJ · kg^{-1} during the second exercise period.

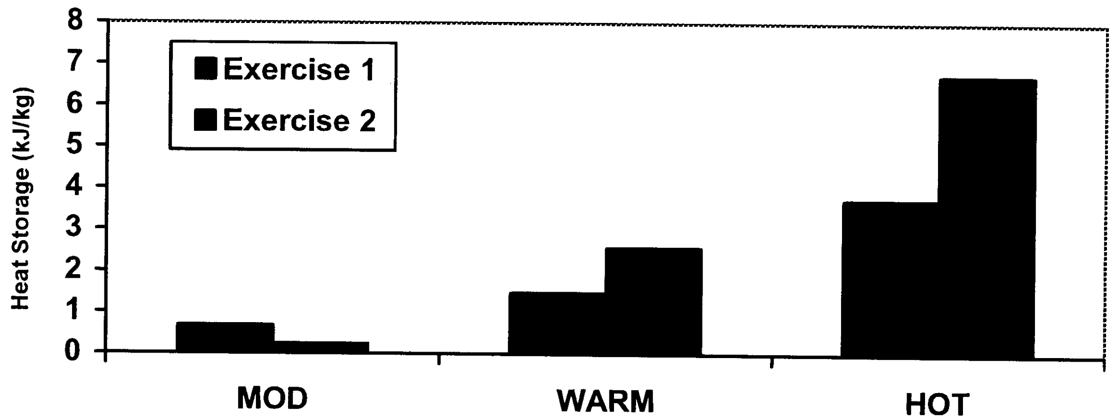

Figure 4. Heat Storage Values During Exercise for MOD, WARM, and HOT

There were significant trial effects for T_O, T_M, and T_I (Table 1). During MOD, exercise FFE temperatures were highest T_I (30.8°C), followed by T_M (29.5°C), and T_O (24.9°C). During WARM, FFE T_O, T_M, and T_I were equivalent (35.6°C). During HOT, FFE temperatures were highest for T_O (45.6°C), followed by T_M (41.5°C), and T_I (40°C).

Sweat loss and fluid intake were significantly greater for HOT compared to WARM and MOD (Table 2).

Table 2. Mean ± S.D. values for fluid intake, sweat loss, urine output, and fluid balance during MOD, WARM, and HOT trials. * HOT significantly greater (p<.05) than WARM and MOD.

Variable	MOD	WARM	HOT
Fluid Intake (L)	0.73 ± 0.36	1.16 ± 0.41	1.78 ± 0.79*
Sweat Loss (L)	-0.62 ± 0.64	-1.05 ± 0.35	-.32 ± 1.12*
Urine Output (L)	-0.26 ± 0.42	-0.13 ± 0.41	-0.06 ± 0.19
Fluid Balance (L)	1.1 ± 1.05	2.08 ± 0.74	3.04 ± 1.39*

Note. Values are mean ± SD. *HOT significantly greater (p<.05) than WARM and MOD.

Discussion

Previous studies have documented the affect of wearing FFE on resting and exercise HR, core and skin temperatures, and physical performance (Pimental, Avellini & Banderet, 1991; Romet & Frim, 1987; Skoldstrom, 1987). Our results confirm the findings of these studies and support the conclusion that wearing an FFE hinders heat dissipation, increases heat storage, and produces greater cardiovascular strain. However, our findings provide new information on body temperature responses of men wearing FFE and performing work/recovery cycles during compensable and uncompensable heat strain.

The impact of wearing FFE on heat stain was most evident during WARM and HOT. During these trials, the average exercise HR differences between the two exercise periods were 23 bpm and 34 bpm, respectively. The higher HR is related to the need to maintain cardiac output and arterial blood pressure during a time of increasing competition between active muscle and skin for blood flow (Nadel, Cafarell, Roberts & Wenger, 1979; Rowell, 1983). The significantly higher sweat loss, fluid intake, and fluid balance evident for HOT compared with WARM and MOD confirms the greater demand on body heat regulation during HOT. Since T_{re} climbed to above 38.0°C, the higher sweat loss for HOT could be related to a resetting of the central set-point temperature (Nielsen, 1984). The higher fluid intake during HOT suggests stimulation of thirst, possibly through the renin-angiotensin system (Greenleaf, Brock, Keil & Morse, 1985).

Previous studies of men wearing vapor-barrier suits and walking continuously in moderate to hot ambient temperatures showed that T_{re} and T_{msk} near the end of the exposure were directly related to T_{db} (Shvartz & Benor, 1972). The significant trial effect for T_{re} and T_{msk} found in our study supports this relationship. However, we also found a significant trial-by-exercise period interaction effect for T_{re} and T_{msk}, suggesting that the work/recovery cycles affected body temperatures.

The significant trial effect and significant trial-by-exercise period interaction effect for T_{re} and T_{msk} suggests that changes in body position, skin blood flow, and ambient temperatures associated with the two work/recovery cycles affected HS. During MOD, exercise T_{re} and T_{msk} were similar between the two exercise periods and only slightly above those for the preexposure rest and recovery periods. In addition, the difference between T_{re} and T_{msk} was about 3°C throughout rest, work, and recovery periods. These responses and the positive T_{db}-FFE temperature gradient indicate that heat strain during MOD was compensable. However, during WARM, T_{re} was about 1°C above T_{msk} during exercise, while the difference was about 3°C between the exercise and recovery periods. Also, T_{re} increased 0.4°C from the first to second exercise periods, while T_{msk} remained unchanged. During HOT, T_{msk} rose about 0.5°C above T_{re}, but this situation was reversed during the subsequent recovery period when T_{msk} dropped about 2°C below T_{re}. During HOT, T_{re} and T_{msk} increased 0.8°C and 0.6°C, respectively, from the first to the second exercise period. The significant trial-by-exercise period interaction effect for T_{re} and T_{msk} reflect an increase in HS due to the two work/recovery cycles. The progressive increases in T_{re} and T_{msk}, reduced differences between the core and skin temperatures, and the negative T_{db}-FFE temperature gradient indicate that heat strain experienced by the subjects during WARM and HOT was uncompensable. The restriction of evaporative cooling by the ambient water vapor pressure (50% RH), lack of air movement within and around FFE, and impedance of water vapor diffusion from the skin through FFE, likely contributed to a decrease in evaporative sweat efficiency and a increase in heat strain during WARM and HOT (Candas & Hoeft, 1995).

Our finding for WARM and HOT support the findings from a previous study of men dressed in FFE and performing two work/recovery cycles in hot air (Ramirez, Hagan, Shannon & Bennett, 1995). Our findings also support the findings of uncompensable heat strain in men wearing a vapor-barrier suit and conducting intermittent work of repeating 10-min exercise-rest patterns in hot air (Kaning & Gonzalez, 1991). Collectively, these findings suggest that work/recovery cycles accelerate HS. The increase in HS associated with work/recovery cycles appears to be related to increases and decreases in skin blood flow accompanying work and recovery, respectively. During exercise, increases in body temperatures would increase skin blood flow in an attempt to reduce HS, while during recovery, the change from exercise to seated rest, and from exposure temperature to cooler air, would decrease skin blood flow and force warm peripheral blood into the body core. This explanation is supported by the increases in T_{re} during the recovery periods of WARM and HOT.

The results of this study showed a significant trial effect for T_O, T_M, and T_I FFE temperatures. However, the exercise period effect for the FFE temperatures was nonsignificant. The FFE temperatures along with the skin temperatures provide information on heat loss and heat gain during exercise in the three environmental conditions (Figure 5).

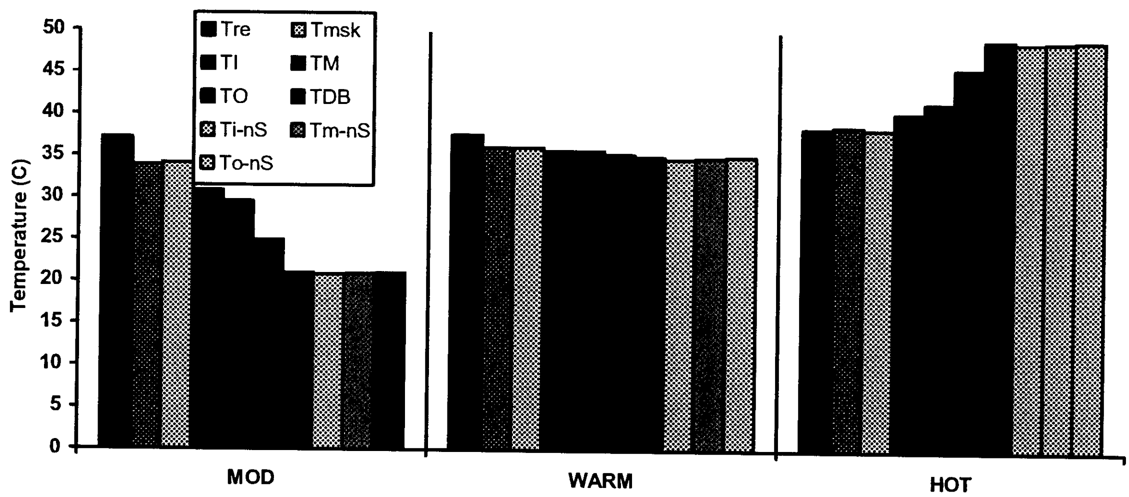

Figure 5. Mean rectal, mean skin, FFE temperatures and FFE alone at the end of the second exercise period for MOD, WARM, and HOT.

During WARM, T_{msk}, T_O, T_M, T_I, and T_{db} were comparable during both exercise periods. The similarity between these temperatures, along with the gain in T_{re} and HS during the second period, indicates that body heat loss was compromised. During MOD, on the other hand, exercise T_{msk} was the highest temperature, followed by T_I, T_M, T_O, and T_{db}. The gradient of these temperatures indicates that body heat was flowing from the skin through FFE clothing layers to the chamber air mass. However, during HOT, T_{db} was the highest temperature, followed by T_O, T_M, T_I, and T_{msk}. This gradient and the increases in the T_{re} and T_{msk} indicate that heat was moving from the chamber air mass through FFE to the skin and body core. However, it is possible that the chamber air RH (50% RH for all trials) and FFE microclimate humidity (Faff & Tutak, 1989) contributed to T_{msk}. In the study by Faff and Tutak, it was reported that FFE microclimate humidity is elevated with exercise and heat exposure. In our study, we also observed that all undergarments (underwear and coveralls) worn by the subjects were saturated with sweat during WARM and HOT. These observations suggest that the FFE reduces evaporative sweat efficiency (Candas & Hoeft, 1995; Kwon, Kato, Kawamura, Yuichi & Tokura, 1998). Thus, our findings suggest that skin temperatures are related to the T_{db}-FFE temperature gradient, and to the rise in body core heat and expansion of this heat volume to the periphery.

During each trial, we also recorded garment temperatures in FFE free of the human subject. During these tests, T_O, T_M, and T_I quickly became equivalent to one another and to T_{db}. However, these FFE temperatures were different from FFE temperatures when occupied by a human body. During WARM and HOT, T_O, T_M, and T_I were lower, while during MOD, T_O, T_M, and T_I were higher compared to those of the instrumented FFE alone. These results suggest that the rates of FFE temperature equilibration for MOD and HOT were reduced by the presence of a human body. This finding suggests that the presence of a physically active human body inside the FFE decreases air mixing between the skin and the inner FFE layers, within the various FFE garment layers, and between the outer FFE and ambient air mass. These changes suggest that wearing FFE while physically active reduces the ambient air-to-skin gradient and increases the effective insulation of the FFE (Nielsen, Olesen & Fanger, 1985). Support for this finding comes from studies (Lotens & Havenith, 1991) showing that clothing insulation is increased by physical activity.

The lower FFE temperatures during WARM and HOT compared to those of the instrumented FFE alone have implications for future FFE designs. The findings from studies of physiological responses while wearing an FFE show that the FFE hinders heat loss. This is not surprising, since the FFE is designed to provide protection against heat and flames. However, the reduced rate of temperature equilibration within FFE in the presence of a human body suggests that future FFE could be designed to provide a greater buffering capacity to heat flow from the ambient air mass. This would reduce the rate of heat flow to the skin and reduce the rate of HS. This alteration in the rate of heat flow through FFE could be accomplished by increasing the number of garment layers within FFE or by constructing within the various FFE garment layers encapsulated air or gas spaces containing high-density gases or heat-absorbing compounds.

The findings from this study suggest the measures collected here may have application to the construction of models predicting rectal temperature responses during firefighting. The temperature gradients within FFE were consistent with expected direction of heat flow given the exercise and environmental conditions. Additionally, HR response has been shown to be an indicator not only of metabolic rate (Webb, Troutman & Annis, 1970), but also of body heat gain (Epstein, Sapiro & Brill, 1983). Further studies are needed to answer this question.

Conclusions

Our findings suggest that exercise T_{re} when wearing FFE is related to T_{db} and HS. When T_{db} is above skin temperature, exercise skin temperatures are primarily related to the T_{db}-FFE temperature gradient. When T_{db} is lower than skin temperature FFE temperatures are dependent on the skin temperature-T_{db} gradient. However, work/recovery cycles accelerate modified body temperature responses. FFE garment temperatures without the presence of a human body rapidly equilibrate with T_{db}. These findings suggest that FFE temperatures change slowly during exercise because air movement within and around the FFE is hindered in the presence of a human body. This information may predict stay times during exposure to extreme conditions. This information has implications for the development of future FFE designs and the construction of heat strain models.

Glossary

FFE = firefighter ensemble

RH = relative humidity (%)

T_{db} = dry-bulb temperature (°C)

MOD = 21°C T_{db} air temperature with 50% RH

WARM = 35°C T_{db} air temperature with 50% RH

HOT = 49°C T_{db} air temperature with 50% RH

HR = heart rate (beats per minute; bpm)

T_{re} = rectal temperature

T_{ch} = chest temperature

T_{ar} = arm temperature

T_{th} = thigh temperature

T_{ca} = calf temperature

T_{msk} = mean skin temperature

T_{oc} = outer FFE chest region temperature

T_{ot} = outer FFE thigh region temperature

T_{mc} = middle FFE chest region temperature

T_{mt} = middle FFE thigh region temperature

T_{ic} = inner FFE chest region temperature

T_{it} = inner FFE thigh region temperature

T_O = average outer FFE temperature

T_M = average middle FFE temperature

T_I = average middle FFE temperature

HS = body heat storage

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14. ABSTRACT (maximum 200 words)

The purpose of this study was to evaluate the relationships among FFE temperatures and body temperatures during exercise in moderate, warm and hot air temperatures. Male subjects (n=10) attempted three trials of 20-min rest, 20-min exercise, 20-min recovery, 20-min exercise and 20-recovery. Subjects wore complete FFE and respired using a positive-pressure breathing apparatus. Exercise treadmill walking (1.1 $m \cdot s^{-1}$/0% grade), occurred in 50% relative humidity (RH) and dry-bulb (T_{db}) temperatures of 21°C (MOD), 35°C (WARM) , and 49°C (HOT), while seat rest and recovery occurred in 27°C air. All subjects completed the test during the MOD and WARM trials. Only 4 subjects completed the HOT trials. ANCOVA revealed (1) significant trial, exercise period, and trial-by-exercise period effects for HR, T_{re}, and HS; (2) significant trial and trial-by-exercise period effects for T_{msk}; and (3) significant trial effects for T_0, T_M, and T_1 FFE temperatures. Our findings suggest that exercise T_{re} in subjects wearing FFE is related to dry-bulb temperature and heat storage. This information may predict stay times during exposure to extreme conditions. This information has implications for the development of future FFE designs, and the construction of heat strain models.

15. SUBJECT TERMS
thermal physiology, rectal temperature, firefighters, modeling, exercise, heat exposure

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